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Economic and Environmental Considerations for Zero-emission Transport and Thermal Energy Generation on an Energy Autonomous Island

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ABSTRACT

The high cost and environmental impact of fossil-fuel energy generation in remote regions can make renewable energy applications more competitive than business-as-usual scenarios. Furthermore, energy and transport are two of the main sectors that significantly contribute to global greenhouse gas emissions. This paper focuses on the generation of thermal energy and the transport sector of a fossil fuel-based energy independent island in Greece. We evaluate (1) technologies for fully renewable thermal energy generation using building-specific solar thermal systems and (2) the replacement of the vehicle fleet of the island with electric and hydrogen-fueled vehicles. The analysis, based on economic and environmental criteria, shows that although solar thermal decreases greenhouse gases by 83%, when compared to the current diesel-based situation, it only becomes economically attractive with subsidy scenarios equal to or higher than 50%. However, in the transport sector, the sum of fuel and maintenance costs of fuel-cell and electric vehicles is found to be 45% lower than that of the current fleet, due to their approximately seven times lower fuel cost. Lastly, it will take approximately six years of use of the new vehicles to balance out the emissions of their manufacturing phase.

Keywords: energy independence, electric cars, fuel-cell cars, solar energy, hydrogen, thermal energy

INTRODUCTION

Fossil fuels are an integral part of numerous aspects of our lives with significant environmental consequences. The generation of electricity and thermal energy are responsible for 25% of the global greenhouse gas emissions (IPCC, 2014). Furthermore, the transport sector is associated with approximately 14% of the global greenhouse gas emissions and 22% of the global carbon dioxide emissions (IPCC, 2014; United Nations, 2015). The expected population rise will unavoidably result in an increase of energy demand and vehicle use. Light-duty vehicles are predicted to increase significantly by 2050, which implies a strong increase in fuel consumption and pollution related to the transport sector (Tagliaferri et al., 2016). Alternative fuels and technologies to decrease the generated greenhouse gas emissions in the energy and transport sectors are widely studied.

Renewable energy sources present an alternative to the current fossil-fuel based status. However, their relatively high costs and intermittent operation makes their applications more demanding and complex. Regions without easy access to fossil fuels due to their remote location or costly conversion processes can constitute good application cases for renewable systems (Petrakopoulou, 2016). This study examines the case study of Skyros, a non-interconnected island in the Aegean Sea in Greece (Petrakopoulou, 2015b). The island is energy independent because it is not connected to the main electrical grid of Greece, but it relies heavily on the combustion of diesel.

Table 1. Characteristics of solar thermal collectors available in the market

Motion	Collector type	Concentration ratio	Temperature range [°C]
Stationary	Flat plate collector	1	30-200
	Evacuated tube collector	1	50-200
	Compound parabolic collector	1-5	60-300
Single-axis tracking	Linear Fresnel reflector	10-40	60-250
	Parabolic trough collector	15-45	50-400
	Cylindrical trough collector	10-50	60-300
Two-axes tracking	Parabolic dish reflector	600-2,000	100-1,500
	Heliostat field collector	300-1,500	150-2,000

We investigate (1) the substitution of the diesel-based space heating requirement of Skyros with solar energy systems and (2) the replacement of the vehicles of the island with zero emission vehicles.

Energy efficiency measures in buildings involve measures related to the building envelope (e.g., thermal insulation, reflective/green roofs), internal conditions (e.g., internal heat loads due to lighting and appliances) and building services systems (e.g., heating, ventilation). Thermal insulation is less effective in cooling-dominated buildings that have large internal heat loads in warmer climates and over-insulation that may increase energy requirements for space cooling should be avoided. Reflective/green roofs may present conflicting space requirements with other renewable energy technologies (e.g., photovoltaic, solar thermal water heaters and district heating/cooling) (Devabhaktuni et al., 2013; Grossmann et al., 2014; Hoppmann et al., 2014; Shi and Chew, 2012).

Solar thermal is very important in the residential sector. The thermal energy from a solar collector can be used in space heating, water heating, steam generation or stored in thermal storage for later use. Depending on solar intensity and location, it is expected that the cost of solar thermal energy will fall from 61-122 $/MWh in 2007 to 22-44 $/MWh in 2050 (Kamel and Fung, 2014). Some characteristics of solar thermal collectors based on their motion are shown in **Table 1** (Allouhi et al., 2015). The storage tank is an important part of the solar water heating system, generally constructed using steel, concrete, plastic, fiber glass or other materials (Shukla et al., 2013). Phase-changing materials can reduce the thermal energy loss in either pipe or duct networks and the initial cost because they do not need insulation and storage tanks and thus save space (Sharif et al., 2015).

The proposed system in this work for the renewable thermal energy generation on Skyros includes vacuum-tube solar collectors, geothermal energy only for water pre-heating purposes and radiant floors (Koroneos and Tsarouhis, 2012). The system includes a hot water storage tank.

While second-generation biofuels present an overall promising potential to decrease emissions in the transport sector, the biomass potential from the agricultural activities of Skyros is relatively low. A more suitable solution would be to generate biofuels from municipal organic waste, and more specifically, household food waste (Matsakas et al., 2014). Accounting for the fact that the quantity of food waste is continuously increasing, while its disposal causes environmental problems, such as greenhouse gas emissions and water contamination, its further utilization in energy applications becomes even more attractive. However, in addition to the fact that the utilization of food waste faces significant challenges related to technological and social issues, its composition varies significantly from place to place and resource to resource. To realize a representative study on waste utilization on Skyros the food waste composition must be first researched and examined in the lab in order to choose the appropriate technology for biofuel generation. For this reason, biomass-based applications in the transport sector are not considered here.

Alternatives for decreasing the greenhouse gas emissions in the transport sector include the use of biofuels in convectional vehicles and the introduction of electric or fuel-cell vehicles. Electric vehicles can be fully electric, hybrid or plug-in hybrid electric (Canals et al., 2016; Grandell et al., 2016). Fully electric cars have only an electric motor, while hybrid vehicles can run on both electric and conventional motor. Plug-in vehicles can load their batteries using electricity from the grid. Fuel-cell cars use hydrogen to generate electricity. It has been shown that heavy metals in battery manufacturing and other aspects of the battery lifecycle increase the environmental impact of this type of cars (Tagliaferri et al., 2016).

In this study, conventional vehicles on the island are substituted by electric and fuel-cell vehicles (Koroneos and Tsarouhis, 2012).

In past work, several scenarios for stand-alone renewable-based energy conversion systems were proposed for covering the electricity needs of the island. It is assumed that electricity-based space cooling, water heating systems and electric cars studied here will be supplied by the proposed stand-alone renewable power stations. In addition, the hydrogen used in the fuel-cell cars is also assumed to be a byproduct of the renewable power stations.

THERMAL ENERGY

The housing sector is a promising area for implementing energy improvement measures on Skyros, since approximately 64% of the buildings on the island were built before 1980, i.e., before the law on thermal regulation had been introduced in the country. Public buildings housing hospitals, schools, military and public/municipal services also offer a relatively good potential for energy reduction on Skyros. Hotels, on the other hand, have a lower overall potential for improvement mainly due to the limited infrastructure available on the island. The analysis presented here includes all of the different property types of the island.

It should be mentioned that the performance of a thermal system depends strongly on the condition of each property type. Based on the year of construction and used materials, a building can be classified into a different class of energy effectiveness. An important way to minimize heat losses or gains in buildings is adequate thermal insulation, represented by the overall heat transfer coefficient of materials (U-values). This factor has been improving in all European countries, especially in the last decades (Baker, 2011; Buildings Performance Institute Europe, 2011). However, the insulation of buildings has been improving throughout the years not only because of the improvement of building materials, but also due to the introduction of new laws. According to the registry of buildings in 2000 (Hellenic Statistical Authority -ELSTAT, 2008), 35.1% of the buildings on Skyros were built with concrete 34.9% with bricks/concrete blocks and 27.6% with stone. In this analysis, all buildings are assumed to perform in a similar manner. In addition, it is assumed that the proposed renewable system achieves total coverage of the space-heating thermal energy requirement.

Technology Proposal and Evaluation

Skyros is shown to have a medium potential priority for woodfuel exploitation (Caralis and Emmanouilidis, 2009), which implies that the installation of new efficient and relatively economic woodstoves could be considered. However, although biomass may be considered a carbon-neutral fuel, its net emissions depend strongly on the applied processing procedure preceding its use. For the purpose of the analysis presented here, it was decided to propose and evaluate a system that does not generate greenhouse gas emissions during its use.

The main parts of the proposed system are shown in **Figure 1**. Those are vacuum-tube solar collectors (Σ1), a solar heat exchanger (Σ2), the recirculation of the water return (Σ4), a geothermal heat exchanger (Σ5), used only for water pre-heating purposes, and a radiant floor system (Σ3) (Koroneos and Tsarouhis, 2012). The evaluated tube collectors are expensive relative to other alternatives but they are efficient, durable and have a longer lifetime. The sizing of the solar-thermal system depends on the surface area of the space that needs to be heated. For example, the mean surface area of residences (66.4 m^2) is covered with solar collectors of a total surface area of 34 m^2, i.e., 9 units of 30-tube solar collectors (of 3.7 m^2 each), and a hot water storage tank with a capacity of 1,300 l. The temperature of the hot water in the reservoir is 59 °C and 42 °C in the floor system.

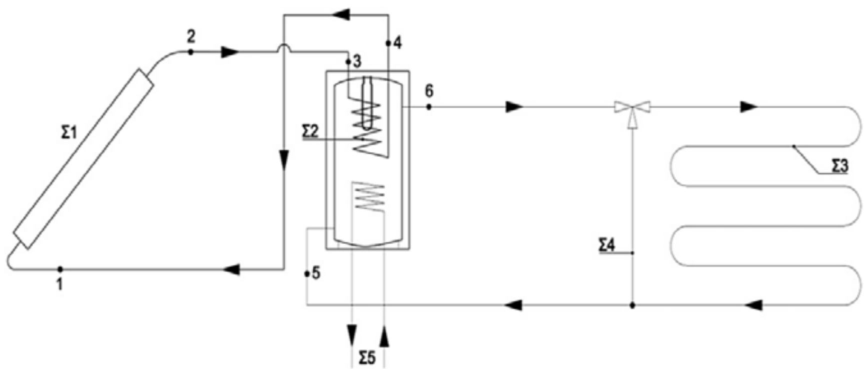

Figure 1. The analyzed solar-thermal system (Koroneos and Tsarouhis, 2012)

The annual thermal energy required, the associated costs and CO_2 emissions on Skyros can be seen in **Table 2**. The energy consumed in each settlement of the island is presented in **Table 3**. Based on the energy needs and the quantity of each property type, the total number of solar-thermal systems required are estimated and shown in **Table 4**.

To number of solar-thermal systems required for implementation in residences are calculated accounting for only buildings with central heating. **Table 4** shows the estimated number of residences with central heating - calculated as a constant 30% of the total residences in each settlement of the island. The remaining information of the table on the number of businesses, schools etc. are extracted from statistical information about the island published by ELSTAT.

Table 2. Thermal energy requirements on Skyros, associated costs and CO_2 emissions

	Residences	Schools	Hospital	Airport	Military bases	Offices/ shops	Restaurants/ bars	Touristic accommodations	Total
Space heating [MWh/a]	6,804	167	159	79	1,116	2,041	323	156	**10,846**
Diesel oil needed [t/a]	572	14	13	7	94	172	27	13	**912**
Cost of fuel [€/a]	689,835	16,952	16,167	8,003	113,172	206,942	32,726	15,862	**1,099,659**
CO_2 emissions [t/a]	1,814	45	43	21	298	544	86	42	**2,892**
Water heating [MWh/a]	1,670	0	0	0	0	0	0	142	**1,812**
Diesel oil needed [t/a]	140	0	0	0	0	0	0	12	**152**
Cost of fuel [€/a]	169,292	0	0	0	0	0	0	14,368	**183,661**
CO_2 emissions [t/a]	445	0	0	0	0	0	0	38	**483**

Table 3. Thermal energy consumption for space heating in each settlement

	Residences [MWh]	Schools [MWh]	Hospital [MWh]	Airport [MWh]	Military bases [MWh]	Offices/ shops [MWh]	Restaurants/ bars [MWh]	Tourist accommodations [MWh]	Total [MWh]
Aspous	243	0	0	0	0	73	12	27	**354**
Atsitsa	30	0	0	0	0	9	1	2	**42**
Acherounes	148	0	0	0	0	44	7	9	**208**
Achilli	120	0	0	0	0	36	6	0	**162**
Kalamitsa	98	0	0	0	0	29	5	11	**143**
Kalikri	98	0	0	0	0	29	5	0	**132**
Kira Panagia	0	0	0	0	0	0	0	0	**0**
Linaria	264	0	0	0	0	79	13	4	**360**
Loutro	64	0	0	0	0	19	3	2	**88**
Molos	1,404	12	0	0	0	421	67	87	**1,992**
Nifi	70	0	0	0	0	21	3	0	**95**
Pefkos	55	0	0	0	0	16	3	0	**73**
Sarakinon (islet)	0	0	0	0	0	0	0	0	**0**
Skyropoula (islet)	0	0	0	0	0	0	0	0	**0**
Skyros	3,766	155	159	0	0	1,130	179	13	**5,402**
Trachi	445	0	0	79	957	134	21	0	**1,636**
Tristomo	0		0	0	159	0	0	0	**159**
Total	**6,804**	**167**	**159**	**79**	**1,116**	**2,041**	**323**	**156**	**10,846**

Table 4. Number of solar-thermal systems in each settlement

	Residences	Schools	Hospital	Airport	Military bases	Offices/ shops	Restaurants/ bars	Tourist accommodations
Aspous	35	0	0	0	0	3	9	12
Atsitsa	4	0	0	0	0	0	1	1
Acherounes	22	0	0	0	0	2	5	4
Achilli	18	0	0	0	0	1	4	0
Kalamitsa	14	0	0	0	0	1	4	5
Kalikri	14	0	0	0	0	1	4	0
Kira Panagia	0	0	0	0	0	0	0	0
Linaria	38	0	0	0	0	3	10	2
Loutro	9	0	0	0	0	1	2	1
Molos	205	1	0	0	0	15	52	39
Nifi	10	0	0	0	0	1	3	0
Pefkos	8	0	0	0	0	1	2	0
Sarakinon (islet)	0	0	0	0	0	0	0	0
Skyropoula (islet)	0	0	0	0	0	0	0	0
Skyros	550	3	1	0	0	40	139	6
Trachi	65	0	0	1	1	5	16	0
Tristomo	0	0	0	0	1	0	0	0
Total	**993**	**4**	**1**	**1**	**2**	**73**	**252**	**70**

Economic Considerations

It is assumed that the economic life of the solar-thermal systems is 20 years and that each 30-tube unit of solar collectors with storage tanks and the associated accompanying components (heat exchangers, etc.) costs 2,000 €. In addition, it is assumed that the radiant floor costs 54 €/m^2 and it covers 40% of the surface area of residences and 80% of the surface area of hospital, schools, offices and shops, the airport, and the military bases. The cost of operating and maintenance of the units is considered to be negligible compared to their investment costs. With the above assumptions, the investment costs of the solar-thermal systems for each settlement are presented in **Table 5**.

Table 5. Potential costs of solar-thermal systems in each settlement

	Residences [€]	Schools [€]	Hospital [€]	Airport [€]	Military bases [€]	Offices/ shops [€]	Restaurants/ bars [€]	Tourist accommo dations [€]	
Aspous	20,175	0	0	0	0	85,137	43,341	263,032	
Atsitsa	86,979	0	0	0	0	26,997	47,383	21,919	
Acherounes	434,896	0	0	0	0	134,983	236,917	87,677	
Achilli	354,608	0	0	0	0	110,063	193,178	0	
Kalamitsa	287,700	0	0	0	0	89,296	156,730	109,597	
Kalikri	287,700	0	0	0	0	89,296	156,730	0	
Kira Panagia	0	0	0	0	0	0	0	0	
Linaria	776,122	0	0	0	0	240,893	422,805	43,839	
Loutro	187,340	0	0	0	0	58,147	102,056	21,919	
Molos	4,134,857	86,284	0	0	0	1,283,377	2,252,532	854,853	
Nifi	207,412	0	0	0	0	64,376	112,991	0	
Pefkos	160,577	0	0	0	0	49,840	87,477	0	
Sarakinon (islet)	0	0	0	0	0	0	0	0	
Skyropoula (islet)	0	0	0	0	0	0	0	0	
Skyros	11,086,503	446,647	1,674,726	0	0	3,441,027	6,039,555	131,516	
Trachi	1,311,379	0	0	392,275	2,180,579	407,026	714,395	0	
Tristomo	0	0	0	0	363,430	0	0	0	
Total	**19,336,248**	**532,931**	**1,674,726**	**392,275**	**2,544,009**	**6,080,457**	**10,566,090**	**1,534,352**	**42,661,088**

Table 6. Cost of diesel oil for a 20-year period and investment costs of solar-thermal systems

	Residences	Schools	Hospital	Airport	Military bases	Offices/ shops	Restaurants/ bars	Tourist accommodations	Total
	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]	
Cost of fuel	13,796,696	339,031	323,350	160,053	2,263,449	4,138,846	654,520	317,234	**21,993,178**
Solar-thermal									
No subsidies	19,336,248	532,931	1,674,726	392,275	2,544,009	6,080,457	10,566,090	1,534,352	**42,661,088**
30 % subsidy	13,535,373	373,052	1,172,308	274,593	1,780,806	4,256,320	7,396,263	1,074,046	**29,862,761**
50 % subsidy	9,668,124	266,466	837,363	196,138	1,272,004	3,040,229	5,283,045	767,176	**21,330,544**
70 % subsidy	5,800,874	159,879	502,418	117,683	763,203	1,824,137	3,169,827	460,306	**12,798,326**

The cost of solar thermal systems is calculated based on the total square meters of the different types of property units and their specific energy consumption (MWh/m^2) relative to residential units. The investment costs of the solar thermal systems are relatively high mainly due to the expensive solar collectors that must be installed. Nevertheless, it should be considered that environmentally friendly measures can be subsidized at a significant percentage by public funds.

Solar-thermal units on properties with a seasonal character (e.g., restaurants/bars and tourist accommodations) or variable operation (e.g., hospital) must be oversized to cover the highest energy needs of each space. In these cases, diesel oil can be used in a more effective manner since it can be consumed only when needed. **Table 6** presents the comparison of the diesel costs and the investment costs of the proposed solar-thermal systems with three subsidy scenarios.

As seen, the investment cost of the solar-thermal systems becomes smaller than the cost of diesel used for space heating purposes with subsidy scenarios equal or higher than 50%.

Environmental Considerations

Since the use of the solar-thermal system is assumed to have zero emissions, the environmental evaluation considers only its production stage. The total weighted impact per kWh generated in the reference system presented in Ref. (Koroneos and Tsarouhis, 2012) is linked to 0.479 g of pollutants. The greenhouse gas emissions of the system are found to be 0.016 g/kWh. In the analysis presented here, the greenhouse gas emissions have been adjusted to the size of the solar thermal systems installed on each property type.

The total annual greenhouse gases of the systems to be installed in each settlement of the island are presented in **Table 7**. It is seen that the total greenhouse gases generated by the production of the solar-thermal systems do not exceed the 0.5 t/a. When looking at the CO_2 emissions (part of the greenhouse gas emissions) of the combustion of diesel currently used for space heating purposes, it is found that they account for somewhat less than 3 t/a. This significant difference shows that greenhouse gas emissions from the production phase of the renewable system are insignificant compared to those of the use phase (combustion) of the diesel oil.

Table 7. Greenhouse gases from the production stage of the solar-thermal systems in each settlement [kg/a]

	Residences	Schools	Hospital	Airport	Military bases	Offices/ shops	Restaurants/ bars	Tourist accommodations	Total
Aspous	1.72	0.00	0.00	0.00	0.00	0.62	0.10	0.70	**3.15**
Atsitsa	0.21	0.00	0.00	0.00	0.00	0.08	0.01	0.06	**0.36**
Acherounes	1.05	0.00	0.00	0.00	0.00	0.38	0.06	0.23	**1.72**
Achilli	0.85	0.00	0.00	0.00	0.00	0.31	0.05	0.00	**1.21**
Kalamitsa	0.69	0.00	0.00	0.00	0.00	0.25	0.04	0.29	**1.28**
Kalikri	0.69	0.00	0.00	0.00	0.00	0.25	0.04	0.00	**0.98**
Kira Panagia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Linaria	1.87	0.00	0.00	0.00	0.00	0.67	0.11	0.12	**2.77**
Loutro	0.45	0.00	0.00	0.00	0.00	0.16	0.03	0.06	**0.70**
Molos	9.95	1.78	0.00	0.00	0.00	3.60	0.57	2.29	**18.18**
Nifi	0.50	0.00	0.00	0.00	0.00	0.18	0.03	0.00	**0.71**
Pefkos	0.39	0.00	0.00	0.00	0.00	0.14	0.02	0.00	**0.55**
Sarakinon (islet)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Skyropoula (islet)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Skyros	26.67	23.19	8.50	0.00	0.00	9.64	1.52	0.35	**69.88**
Trachi	3.15	0.00	0.00	8.42	357.21	1.14	0.18	0.00	**370.10**
Tristomo	0.00	0.00	0.00	0.00	5.01	0.00	0.00	0.00	**5.01**
Total	**48.19**	**24.97**	**8.50**	**8.42**	**362.21**	**17.42**	**2.75**	**4.11**	**476.57**

TRANSPORT SECTOR

The municipality of Skyros possesses certain vehicles that serve the needs of its departments as presented in Table 8 (Municipality of Skyros, 2014). To estimate the number of vehicles on the island, we used general country statistics. Population and car ownership statistics in Greece by the Hellenic Statistical Authority show that approximately one in four people (26%) living in the prefecture of Evvoia, that Skyros is part of, own a private car (Hellenic Statistical Authority -ELSTAT, 2009). This percentage increases on islands, reaching, in some cases, the high percentage of 44%. This depends, however, on the size of the population, the age of the people and their everyday activities. For Skyros a mean value of 34% can be assumed (one in three people own a private car) due to the relatively high percentage of the island's population in young and middle-aged people. Approximately one in six people (16% of the population) can be assumed to own a private truck for farming and/or other purposes.

Table 8. Vehicles of the municipality of Skyros

	Department/service	Type of vehicle	Type of fuel	Fuel consumption threshold [l/month]
1.		Bus FIAT	Diesel	254
2.	Finance Directors	4x4 SUZUKI	Unleaded fuel	135
3.		Motorcycle KAWASAKI	Unleaded fuel	26
4.		Passenger car HYUNDAI	Unleaded fuel	112
1.		Garbage truck MERCEDES	Diesel	1060
2.		Garbage truck MERCEDES	Diesel	592
3.		Garbage truck VOLVO	Diesel	516
4.	Cleaning & Electrolighting	Garbage truck NISSAN	Diesel	625
5.		Truck MERCEDES	Diesel	275
6.		Truck MERCEDES	Diesel	197
7.		Truck RENAULT	Diesel	267
8.		Truck with aerial platform FIAT	Diesel	No limit
9.		Van MAZDA	Unleaded fuel	165
10.	Water Supply Sewerage	Van OPEL	Unleaded fuel	107
11.		Van OPEL	Unleaded fuel	155
12.		Tanker MERCEDES	Diesel	495
13.		Excavator - Backhoe KOMATSU	Diesel	No limit
14.		Grader GREINTER	Diesel	No limit
15.		Crawler loader CATERPILLAR	Diesel	No limit

Technology Proposal and Evaluation

The zero-emission solution this report studies for the transport sector is the replacement of the vehicle fleet of Skyros with electric and hydrogen-fueled vehicles. Although such an action is challenging and cannot happen instantaneously, it is worthy of evaluation and investigation for two primary reasons: electricity for hydrogen generation and for utilization in electric cars can offer (1) a way to stabilize and ensure reliable and more secure

Table 9. Fuel requirement of fuel-cell and electric vehicles

	Private cars	Private trucks	Public vehicles	Total
Number of vehicles	1,027	475	15	**1,042**
Total use [km/a]	1,439,200	1,028,000	5,097	**1,444,297**
Electric vehicles	719	332	11	**730**
Use [km/a]	1,007,440	719,600	3,568	**1,011,008**
Fuel use [kWh/a]	147,086	105,062	521	**147,607**
Fuel cell vehicles	308	143	4	**312**
Use [km/a]	431,760	308,400	1,529	**433,289**
Fuel use [tonnes H_2/a]	13.67	9.77	0.05	**14**
Electricity required [GJ/a]	592,198		53	**592,251**
Hydrogen required [GJ/a]	245,496		36	**245,532**

operation of renewable power stations by using electricity surpluses and (2) an opportunity to use fuels generated from renewable resources that, in contrast to biofuels, do not have direct greenhouse gas emissions.

In the following economic and environmental investigation, it is assumed that 70% of the existing vehicles on Skyros will be replaced with electric cars and 30% with fuel-cell cars. The electric car used as reference is the *Nissan Leaf* that operates on a 24 kWh lithium-ion battery (Nissan, 2016). The hydrogen reference car is the *Hyundai ix35* with a reservoir capacity of 5.63 kg of H_2 (Hyundai Motor Company, 2015). The estimated current vehicles and the proposed fleet are shown in **Table 9**.

Stand-alone renewable power plants evaluated for the case of Skyros were found to generate surpluses of electricity of 6,721 and 2,832 MWh, respectively (Petrakopoulou, Robinson and Loizidou, 2016a, 2016b). With the proposed electrolyzer unit of the plants, 379.4 MWh/a are needed to generate the hydrogen required to fuel the fuel-cell cars. In addition, another 148.0 MWh/a are needed to power the electric cars. The remaining electricity surplus of the plants can be used to generate hydrogen to sell in a potentially mature hydrogen market at the time of the materialization of this proposal. The annual gain through the sale of the generated hydrogen can be used to subsidize the renewable development of the island.

Economic Considerations

A transport sector fully reliant on hydrogen and electric vehicles calls for the complete replacement of the current vehicle fleet of the island and assumes that all technological and operational limitations of the two technologies have already been managed. Furthermore, the purchase and maintenance costs of the new vehicles, involving, for example, the replacement of the car battery, would result in an overall substantial economic expenditure. However, it would provide the opportunity to the inhabitants of Skyros to use efficient, zero-emission cars based on locally-produced fuels.

The fuel costs calculated for the existing public passenger cars of the island can be seen in **Table 10**. Detailed calculations of the fuel consumption can be found in Ref. (Petrakopoulou, 2015a). The specific fuel consumption presented here refers to existing vehicles, the age of which may vary significantly, and is thus not representative of the consumption reported for newer cars with better efficiencies. The hydrogen price used is 5 €/kg. With this price, a newly-built hydrogen station would recoup the costs of the station through the sales of hydrogen within approximately 20 years (Melaina and Penev, 2013). The cost of electricity used in the electric cars is assumed to be that reported for the country in 2014 (0.130 €/kWh) (Eurostat, 2015). The life cycle of the new vehicles is 10 years.

Table 10. Consumption and purchase price of different types of passenger cars

Type of car	Curb weight [kg]	Purchase price [€]	Fuel consumption [MJ/100 km]	Fuel price [€/100 km]	Distance [km]
Current situation*					
Gasoline	-	-	397.64	14.91	-
Diesel	-	-	251.88	7.88	-
Electric	1,493	29,010	59.83	2.31	135
Fuel cell car	1,850	73,385	134.90	4.75	593

**Refers to private passenger cars. The age of the cars varies.*

The main expenditure associated with the proposed cars is their purchase cost (**Table 11**). Although the cost of vehicles will differ depending on their type, use and size, for simplicity a 20% increase for trucks and 50% increase of public vehicles (mainly big trucks) is applied. In the case of the electric vehicles, the cost of the battery of the car also poses an important cost. The battery of the electric cars is assumed to be changed twice in the lifetime of the car (assumed 10 years).

Table 11. Total cost of the new vehicle fleet on Skyros

	Private cars	Private trucks	Public vehicles	Total
Electric vehicles				
Purchase cost [€]	20,858,190	11,557,584	478,665	**21,336,855**
Cost of battery [€/a]	93,470	431,600	14,300	**107,770**
Fuel cost [€/a]	23,283	16,631	82	**23,366**
Fuel cell vehicles				
Purchase cost [€]	22,602,552	12,592,851	440,309	**23,042,862**
Cost of PEMFC* [€/a]	5,063	2,351	66	**5,129**
Fuel cost [€/a]	20,509	14,649	73	**20,581**

* *Proton exchange membrane fuel cells*

As seen in **Table 12**, the total cost of fuel used currently in the transport sector is 319,000 €/a (Petrakopoulou, 2015a). The combined fuel cost of fuel-cell and electric vehicles, on the other hand, is calculated to be 43,947 €/a (**Table 11**), i.e., more than seven times less than that of the current situation based on conventional fuels. The maintenance costs of the new vehicle fleet, however, is found to be approximately 3.6 times higher. Overall, the combination of fuel and maintenance costs of the fuel-cell and electric vehicles is found to be 45% that of the current fleet.

Table 12. Total costs of existing and proposed cars

	Existing cars	Fuel cell and electric cars
Purchase cost [€]	-	44,379,717
Maintenance cost (battery) [€/a]	31,260*	112,899
Fuel cost [€/a]	319,000	43,947

* Assumed price of a typical car battery: 150 €, lifetime: 5 years, replacements: 2 within the 10 years.

Environmental considerations

Gasoline and diesel vehicles, currently used on the island generate the CO_2 emissions shown in **Table 13**. Zero emissions from the transport sector utilizing hydrogen- and electric-based vehicles means the direct reduction of the CO_2 emissions of Skyros by 673 tones annually. This quantity is equal to the annual CO_2 emissions of a 320-kW natural gas plant with an annual capacity factor (percentage of hours of full load operation in a year) of 70%.

Table 13. Annual avoided CO_2 emissions in the transport sector on Skyros

	CO_2 emissions [t/a]		
	Public vehicles	Private vehicles	Total
Diesel	161	147	308
Gasoline	19	346	365

It is assumed that the electricity used in the electric cars and the hydrogen used in the fuel-cell cars are provided by a renewable plant that does not produce harmful emissions. Since the operation of the cars does not generate any emissions either, the use of both the electric and hydrogen cars are considered to generate zero air pollutants and have zero direct greenhouse gas emissions. However, there are emissions generated during the production phase of the cars. The calculated total emissions are shown in **Table 14**. For the purpose of these calculations, it was assumed that trucks have 20% higher air pollutants and greenhouse gas emissions. This percentage was raised to 50% for public vehicles. The intermediate calculations for passenger vehicles only are shown in **Table 15**, while the exact methodology followed is explained in detail in Ref. (Pistoia et al., 2010).

Table 14. Specific emissions of the curb of a typical vehicle [kg/kg]

	CO	NO_X	GHG
Extraction	1.20E-02	5.06E-03	1.93E+00
Manufacturing	1.88E-04	2.40E-03	1.23E+00
End of life	1.77E-06	3.58E-05	1.40E-02
Total	**1.22E-02**	**7.50E-03**	**3.17E+00**

It can be seen that the avoided emissions during the use phase of the new fleet will need approximately six years to balance out the emissions of the manufacturing of the electric- and hydrogen-based cars.

Table 15. Intermediate calculation results for passenger vehicles

	Curb weight [kg]	Battery weight [kg]	Net weight [kg]	Air pollutants battery [kg]	GHG* [kg]	Air pollutants [kg]	GHG car [kg]
Electric cars	1,493	377	1,116	5.40	952.64	5.40	952.6
Fuel cell cars	1850	91	1,759	35.44	5524.53	35.44	5524.5

** Greenhouse gas emissions*

Table 16. Air pollutants and greenhouse gas emissions during the manufacturing process of the electric and fuel cell vehicles

	Air pollutants [t]	Greenhouse gas emissions [t]
Electric vehicles	6	1,080
Fuel cell vehicles	17	2,683
Total	23	3,763

CONCLUSIONS

This paper studied the conversion of the currently fossil-based thermal energy and transport sectors of a non-interconnected island in the Mediterranean into zero emission renewable-based sectors. The analysis includes both economic and environmental considerations.

Thermal energy considerations included a solar system with vacuum-tube solar collectors, a solar heat exchanger, a geothermal heat exchanger used only for water pre-heating purposes, and a radiant floor system. The building sector was a promising area for energy improvements, since a high percentage of the buildings on the island were built without proper thermal insulation. Solar thermal was found to be more expensive than the current diesel-based situation, especially in buildings with a seasonal or variable use. The renewable-based scenario became economically attractive with subsidy schemes equal to or higher than 50% of the cost. Nevertheless, the greenhouse gas emissions of the solar-thermal systems would be significantly lower than those currently generated (0.5 t/a, compared to 3 t/a from the use of diesel).

In the transport sector, it was assumed that 70% of the existing vehicles on the island were replaced with electric cars and 30% with fuel-cell cars. The hydrogen and electricity required were delivered from stand-alone power plants located on the island. The reference electric cars had a 24 kWh lithium-ion battery and the hydrogen cars a reservoir capacity of 5.63 kg of H_2. The sum of fuel and maintenance costs of the fuel-cell and electric vehicles is found to be 45% that of the current fleet. Lastly, it was seen that the avoided emissions during the use phase of the new fleet will need approximately six years to balance out the emissions of its manufacturing phase.

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